Synthetic Multifunctional Materials:
Structure + ...

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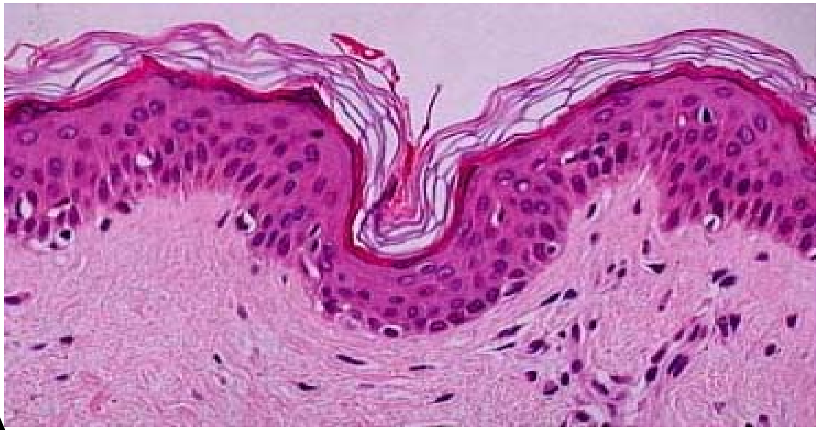
Synthetic Multifunctional Materials: *Goal*

DARPA SMFM - "STRUCTURE + …"



Present

Structure is parasitic to the mission-
It provides platform for sensor, communication, munitions, etc.

Goal

Have No Structure,

OR

Give Structure Other Functions!

Synthetic Multifunctional Materials

What are Synthetic Multifunctional Materials?

Materials that are explicitly designed to realize multiple tasks. (Structure + power generation, + sensing, + self repair, …)

Inspiration

- **Nature's materials (e.g., skin, bone): efficient, responsive, adaptable, self-healing**
- **Emerging materials science base: process and material modeling, engineered microstructures, flexible manufacturing**

Program Objectives

- **Establish formalized design methodologies for multi-functionality**
- **Synthesize multifunctional materials and components and, through compelling challenge problems, demonstrate approach and advantages**
- **Change the design methodology for structures in Defense systems**

The Problem

Fact: <u>Structure</u> constitutes a large fraction of total system weight

System	Total (lb.)	Structure (lb.)	Struct. Fract.	Payload (lb.)	Payload Fract.
Sender	10	5	50%	2	20%
F-18E/F	66,000	34,900	53%	13,700	21%
747-400	800,000	384,500	48%	285,000	36%
Satellite			19%		34%
Microstar (goals)	86 gms.	22.5 gms.	26%	18 gms.	21%

Synthetic Multifunctional Materials:
Pervasive, High Impact Applications in DoD

Soldier systems (weight, weight, weight!!)

Future combat vehicles (weight, survivability, self repair)

Navy platforms (explosion-proof, fire and IR suppression)

Extended range UAVs and micro-UAVs (weight: critical to long loiter time)

Spacecraft (weight/volume, power collection, thermal control & distribution, communication, vibration control)

Hypersonic vehicle skins (weight, thermal control)

Re-usable launch vehicles (weight, thermal protection system)

Synthetic Multifunctional Materials:
Program Vision

System Components

- Load-bearing structure
- Propulsion
- Survivability features
- Power (fuel)
- Payload

Nature's Systems

- **Functions evolved in unison**
- **Components are *multi*functional**

Man-made Systems

- **Functions designed in isolation**
- **Components have a *single* function**

Program will revolutionize the way structures are designed, built and used

Natural Multifunctional Material: *An Example*

Cuticle

A Hetero-nanostructured Material:

(Compositional & Morphological)

Chitin fiber (3 nm x 180 nm -- like glass fibers)
- **orientation**
- **volume fraction**

Protein matrix
- **pH control**
- **water content control**
- **modulus control**

Pore canals
- **connection between epidermal cells and cuticle for communication and repair**

Interlined holes
- **filled with resilin**
- **campaniform sensilla**

Multi-layered arrangement
- **stiffer outer/softer inner layer**

Minnesota wood beetle

Design issues solved by Nature!
- Fiber orientation/placement
- Fiber matrix interaction based on chemical control of interfaces
- **Holes/canals distribution without weakening structure**
- **Self-repair, growth**
- **Temperature control**

Designing Synthetic Multifunctional Materials

Nature does extremely well but …

- **Evolved through "trial and error" with eons of experiments**

Revolutionary value of SMFM to Defense applications depends on:

- **Achieving synergistic, not parasitic combination of properties**
- **Ability to design efficient multifunctional structures in engineering-compatible time frames!**

Need to combine understanding of nature with advances in materials science

Synthetic Multifunctional Materials:
Solving the Challenge Problem(s)

- Select ~3 multi-disciplinary teams
  - * Allow them to set their own challenge problem (but meeting strict multifunctionality requirements!)
  - * Force multi-disciplinary approach (industry, Government, universities)
  - * Insist on definitive milestones and deliverables
- Encourage non-competitive interaction across teams (e.g., university activities)

Synthetic Multifunctional Materials:
Program Plan

1. Establish design methodologies for synthetic multifunctional materials
   - Extract and selectively exploit lessons from nature
   - Establish approaches, rules and tools for optimization of multiple functions into man-made structures
2. Synthesize, process and fabricate novel multifunctional materials/components to solve compelling challenge problems
   - Lead by example: change the way structures are designed, built and used
   - Demonstrate multi-functionality value to DoD systems

Synthetic Multifunctional Materials:
Development of SMFM Design Methodologies

Materials Characteristics

Mechanical	Stress - Strain
Thermal	Heat Flux - Temp. Gradient
Electric	Flux Density - Field Intensity
Magnetic	Flux Density - Field Intensity
Ballistic	Energy Density-HSR response
Repair	????

Research Issues

Multi-phase multi-component geometric arrangements

Transition from micro to macro scales

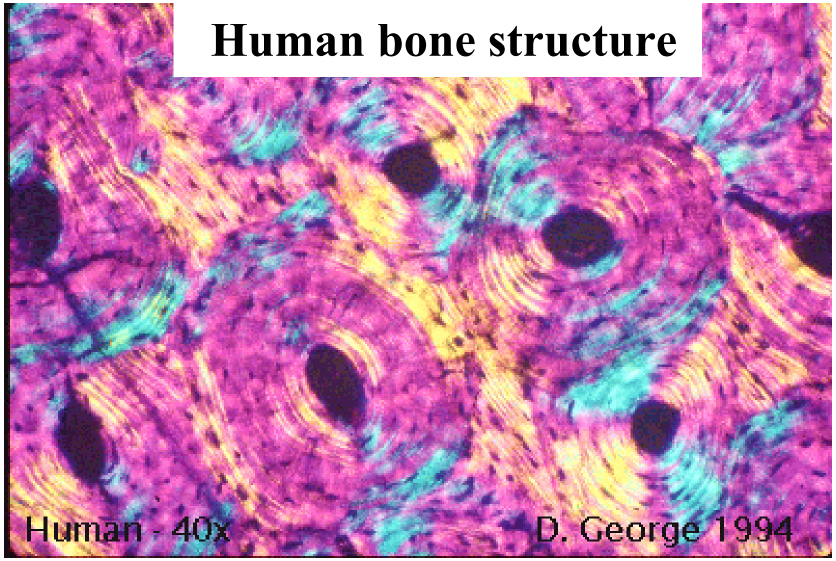
Competing linear and nonlinear responses

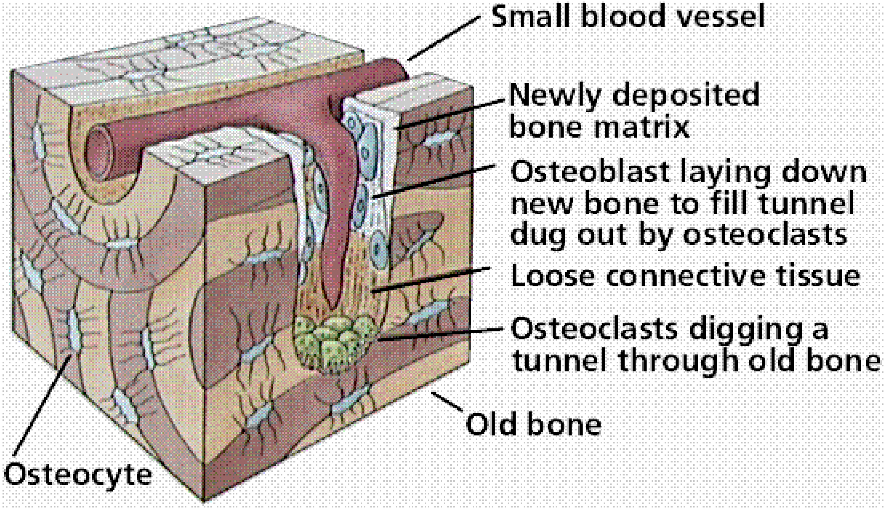
Anisotropic behavior

Discreet vs. continuous properties

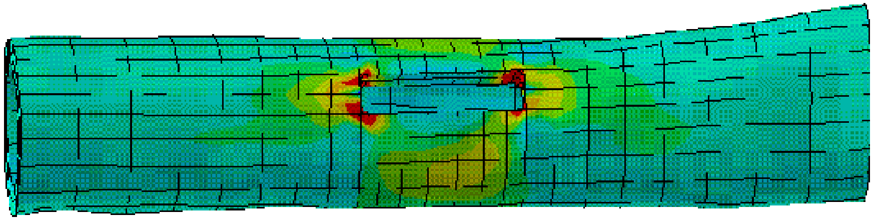
Major Challenge: Integration of diverse features/requirements into useful materials and design tools

Nature's Example: *Self-Repairing Materials (Bone)*



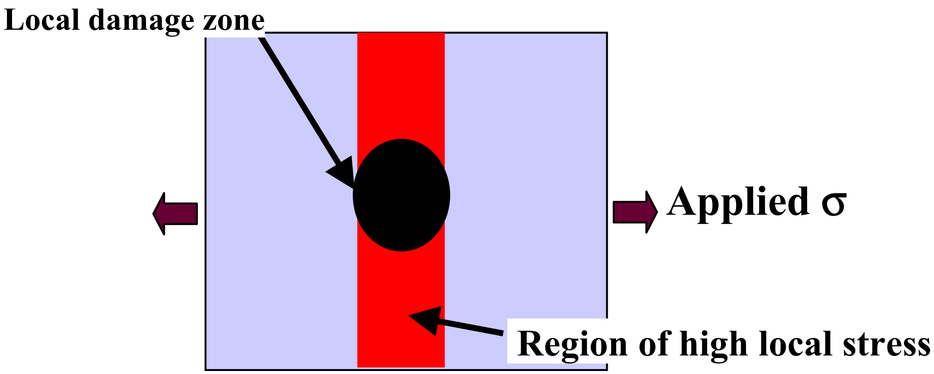


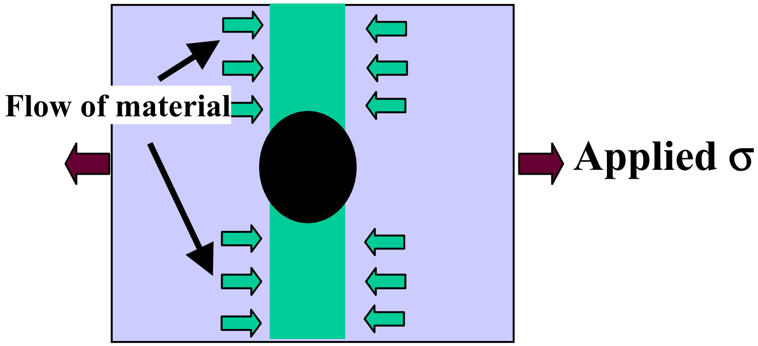
Growth as a function of SED



- **Newly formed bone is stiffest adjacent to regions of high strain energy density (SED)**
- **Mechanical deformation immediately results in a transient increase of Ca^{2+} levels which initiate at the [damage] site and propagate throughout the cell and to neighboring undamaged cells.**

SMFM Example: *Self-Repairing Materials*





Idea

- Mechanical loading or damage causes local high stress/strain
- Material flows, precipitates or re-aligns to region of high stress/strain

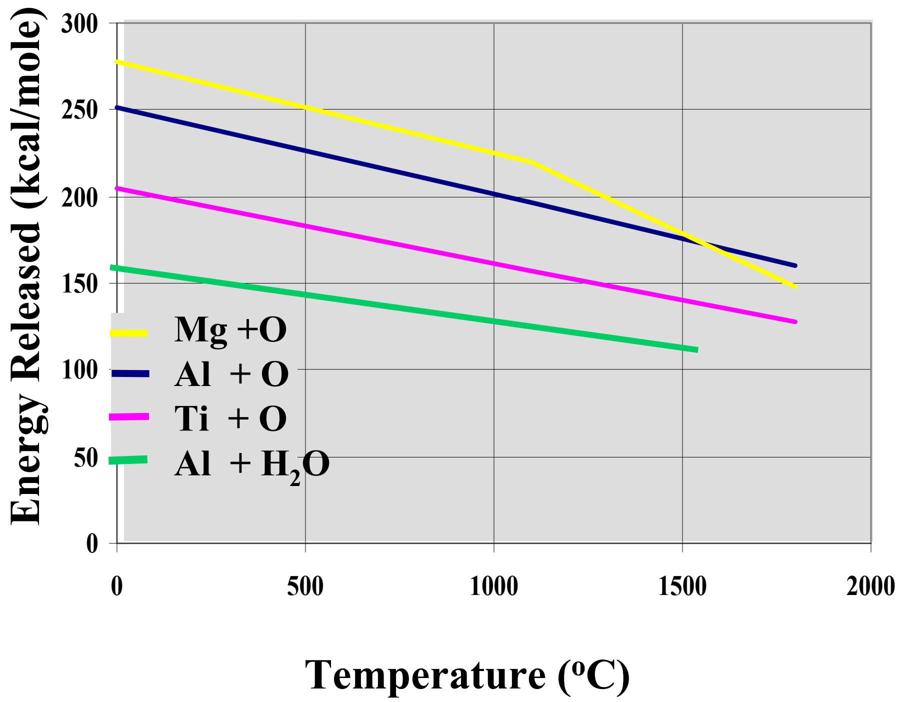
Inspiration

- Healing and strengthening of natural systems (wood/bone)

The existence of inorganic examples of stress-induced transformations make this possible

SMFM Example: *Structure as a Fuel*

Air/water-breathing Systems



- **Structure represents stored energy**
- **Conversion to oxide employs "free" air or water, e.g.,**
  - **vortex combustor, (Penn State)**
  - **autophagous vehicles (NRL)**
  - **self-consuming satellites (LM)**

The structure is a mine of energy!

Synthetic Multifunctional Materials:
*Armor Systems**

ANTIARMOR DEFEAT/ SIGNATURE MANAGEMENT/ INTEGRATED STRUCTURE

Multifunctional Materials

- Signature Management
  - Suppression
  - Camouflage
- Armor
  - Energy Absorption
  - Momentum Reduction
  - Path Deflection
  - Catch-All
- Structural Performance
  - Strength
  - Environ. Protection
  - Self-healing

Multifunctional Design Tools

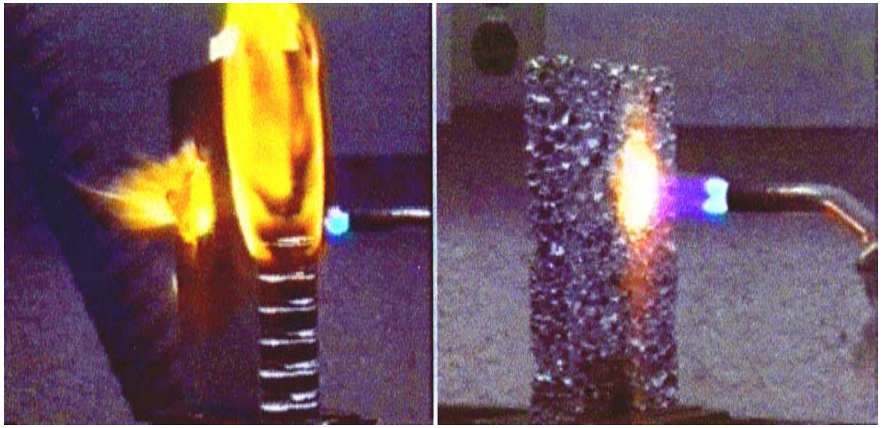
- Integration
  - Functions
  - Structure
- Materials
  - Selection
  - Properties
  - Trade-offs
- Definition
  - Environments
  - Performance
  - Geometry, Attachments

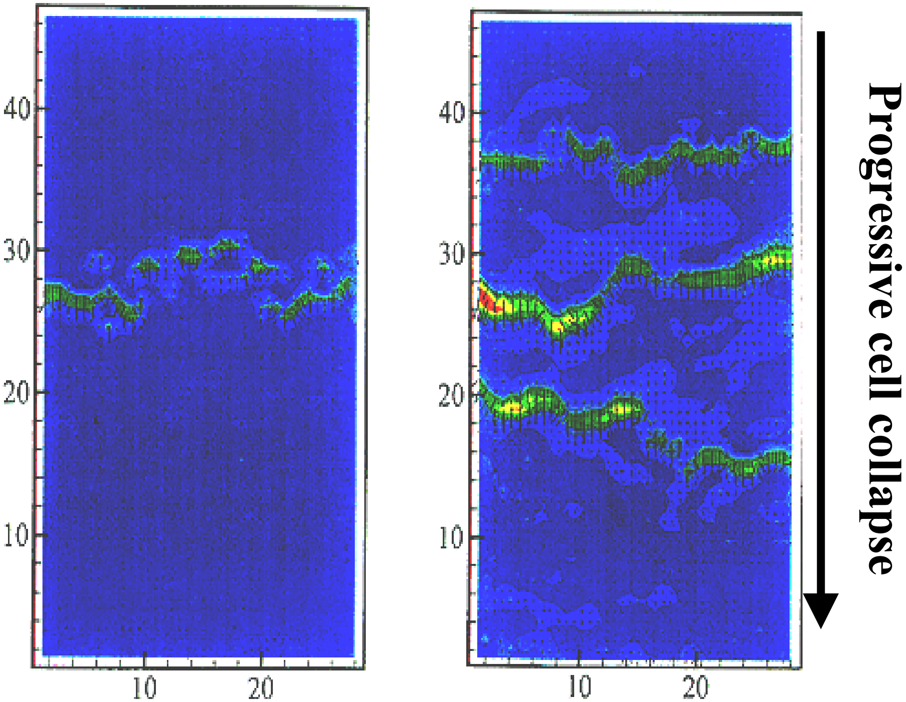
* Adapted from ARO

SMFM Example:
Multifunctional Ultra-light Porous Metals

BLAST SUPPRESSION
- Magazine protection
- Shipboard missile isolation

THERMAL CONTROL
- Heat dissipation
- Magazine fire suppression
- Passive cooled skins





Time = t

Time = t+δt

SMFM Research Issues: Multi-scale integration, non linear response

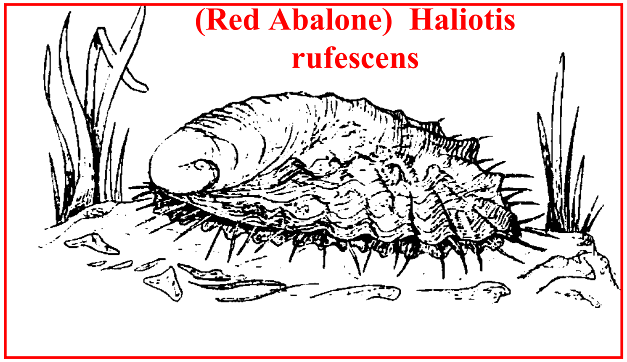
Synthetic Multifunctional Materials:
Program Execution

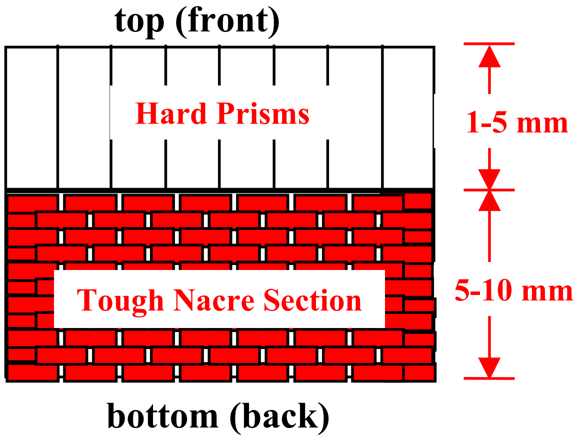
- **Phase I:**
  - **Selection of several SMFM systems**
  - **Proof of principle concepts**
  - **Demonstration of design approach**
  - **Focus on science**
  - **Formalize design methodology**
  - **Downselection**

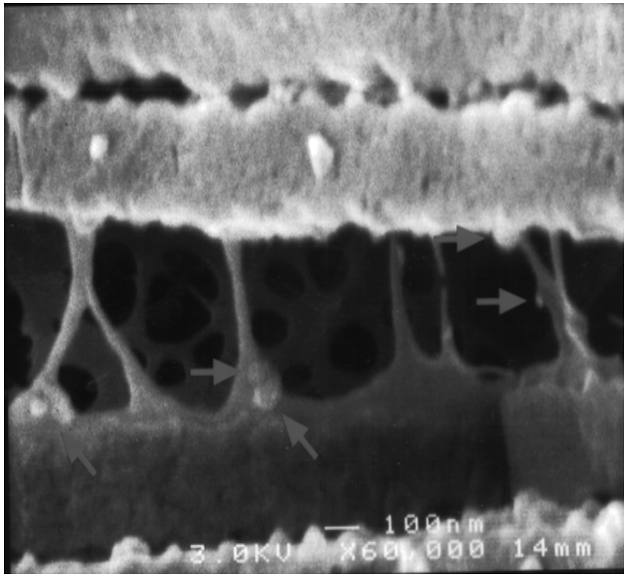
- **Phase II:**
  - **Demonstration of advantages**

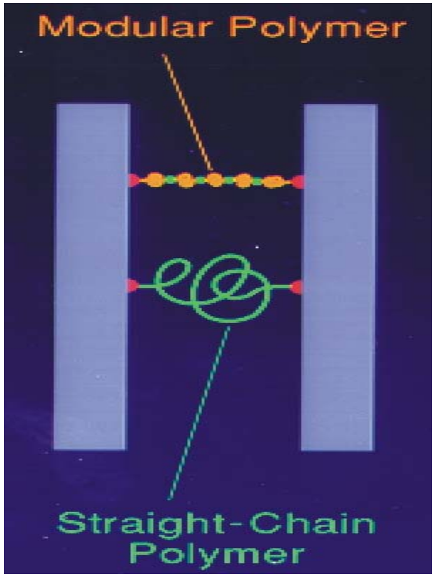
- **Phase I Selection Criteria**
  - **Technical Excellence**
    - **Innovation**
    - **Specific combination of functions**
    - **Likelihood for manufacture**
    - **Need-led development**
  - **Demonstration Opportunity**
    - **Clear tie to a system**
    - **Materials with possible insertion window**

Synthetic Multifunctional Materials:
*Biomimetic Armor**









Natures System

SMFM System

* Adapted from ARO